Benthic Turbulence and Mixing Induced by Nonlinear Internal Waves

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Award Number: N00014-07-1-0957
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LONG-TERM GOALS

The long term goal of this work is to develop a fundamental understanding and predictive capability of the underlying physics of the interaction of nonlinear internal waves (NLIWs) with the continental shelf seafloor over a broad range of environmental conditions. We are particularly interested in how such interactions impact underwater optics and acoustics and shelf energetics and ecology by stimulating enhanced benthic turbulence and bottom particulate resuspension.

OBJECTIVES

The specific objectives of this project are directed towards:

- Characterizing the structure and energetics of the three-dimensional turbulence and mixing in the NLIW-induced time-dependent boundary layer as a function of wave-based Reynolds number and wave amplitude.

- Comparing results of Direct Numerical Simulation (DNS) of NLIW-induced boundary layers with equivalent field observations to:

    - Flesh out the underlying fluid dynamics and, in particular, determine whether global instability of the NLIW-induced boundary layer is operative in the coastal ocean.

    - Provide consistency checks for the DNS along with means for further refining future simulations.

    - Develop predictive tools for designing future deployments focused towards identifying signatures of energetic NLIW-induced benthic events.

APPROACH

Our approach uses Direct Numerical Simulation (DNS) based on a spectral multidomain penalty method Navier-Stokes solver developed by the PI (Diamessis et al. 2005) for the simulation of high Reynolds number incompressible flows in vertically finite domains. The advantages of this computational tool lie in its high (spectral) accuracy, spatial adaptivity (straightforward resolution of

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2007**	2. REPORT TYPE	3. DATES COVERED **00-00-2007 to 00-00-2007**
4. TITLE AND SUBTITLE **Benthic Turbulence And Mixing Induced By Nonlinear Internal Waves**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Cornell University,School of Civil and Environmental Engineering,220 Hollister Hall,Ithaca,NY,14853**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S)
		11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES **code 1 only**		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

the active regions of the flow, i.e. the bottom boundary layer and seasonal thermocline) and lack of the artificial dissipation inherent in commonly used low-order accuracy finite difference schemes which can spuriously diffuse out critical boundary layer physics. To ensure numerical stability while preserving spectral accuracy at Reynolds number values as close as possible to oceanically relevant values, the numerical scheme is buttressed with explicit spectral filtering and a penalty method in the vertical direction.

Our problem geometry considers a wave fixed in a frame of reference moving with the phase speed of the NLIW through a waveguide of *uniform depth*. In this temporally evolving simulation, the Navier-Stokes equations are solved for the perturbation velocity/fields (Diamessis and Redekopp 2006a) with a no-slip bottom boundary condition.

WORK COMPLETED

Funding of the project did not officially begin until mid-July 2007. Nonetheless, in April, we initiated an effort towards forging a closer connection between the dynamics of the erupting NLIW-induced boundary layers observed and analyzed in 2-D numerical simulations and equivalent observations in limited portions of the near-bed measurements made as part of the ONR-funded Coastal Mixing and Optics 1996 (CMO 96) field experiment.

To this end, 2-D DNS data sets spanning a broad range of wave amplitudes (normalized maximum isopycnal displacement) and wave Reynolds number (defined based on oceanic waveguide depth and limiting long wave phase speed) were examined to identify energetic near-bed events, ``benthic eruptions'', where coherent concentrations of elevated vorticity were ejected from the destabilized NLIW-induced boundary layer high into the water column (Figure 1). In parallel, the CMO 96 dataset was scanned and analyzed by Prof. Darek Bogucki of RSMAS, U. Miami. The comparisons performed were clearly between only qualitatively similar wave states. Although the CMO 96 experiment was designed without the benefits of high temporal and spatial resolution, which are only now becoming available through numerical simulations, it is believed that some characteristic features contained within the data set might be advantageously examined in the light of the specific DNS.

Analysis focused on a specific benthic eruption event observed in the DNS and of the near-bed signature recorded by a SeaBASS tripod (Shaw et al. 2001) during a passage of a specific NLIW train consisting of two waves . In the lee of each wave in this train, strong reversals in the horizontal velocity component aligned with the wave's phase speed were observed, indicating boundary layer separation (Figure 3b). The DNS results, computed in a frame of reference moving with the wave's phase speed (i.e. Lagrangian frame), were converted to a Eulerian reference frame that is fixed at the virtual ocean bottom. Twenty Eulerian virtual sensors were placed along the NLIW propagation path and the qualitative comparison was focused on data obtained from a sensor at a location nine waveguide depths downstream of the initial position of the wave. It is this sensor which exhibited one of the most intense benthic eruptions, an eruption accompanied by vortices shed as high as 10% of the total waveguide depth above bottom (Figure 2). The quantity that the comparison between simulations and field observation comparison focused on was the spanwise vorticity, a proxy for benthic transport.

In June, the P.I. visited the Oregon State Ocean Mixing group led by Prof. Jim Moum. Following a presentation, the P.I. engaged in significant discussion with members of the group.The results of this discussion provided invaluable insight towards setting-up three-dimensional simulations of NLIW-induced boundary layers and towards the identifying new approaches in analyzing field data.

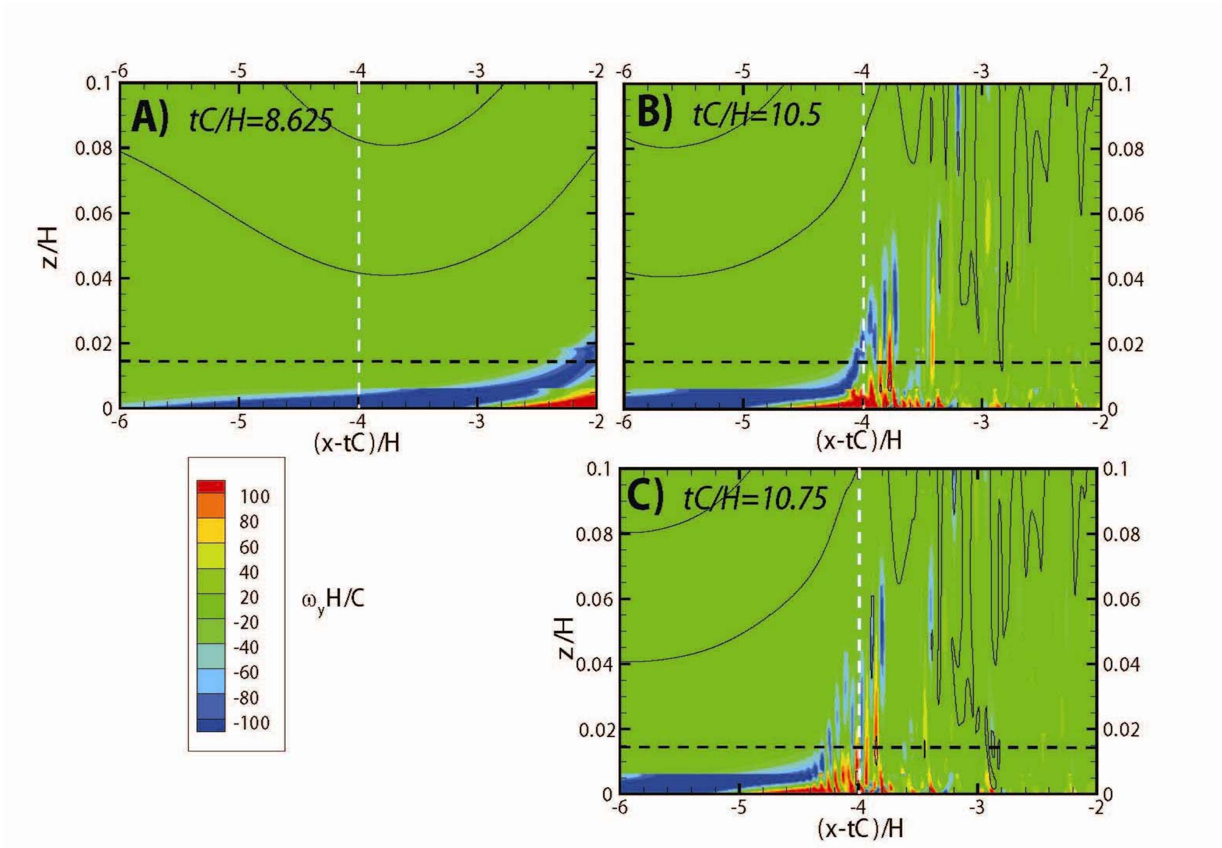

Figure 1: DNS (Lagrangian) results. [Vorticity (color contours) and isopycnals (black line contours) at different simulation times tC/H (C and H are the wave phase speed and water depth, respectively) for the near-bed region under a NLIW of depression at Reynolds number 10^5 and wave amplitude α_0=0.48. The wave propagates from right to left. In the figures A to C, the streamwise coordinate has been translated by –tC/H to represent the corresponding location in a fixed coordinate system. Shown is the bottom 10% of the water column. At t=0, the wave center is located at x/H=5. The horizontal dashed line corresponds to location in the CMO data below which observations are not available. Vertical dashed line shows the position of the virtual Eulerian sensor that provides the depth-time diagram of figure 2.]

RESULTS

Taking into account Reynolds number effects (increased Reynolds numbers lead to thinner NLIW-induced boundary layers, smaller ejected vortex lengthscale and higher frequency of vortex shedding), differences in spatiotemporal resolution and the restriction of the field data to depths between1 and 7 mab, significant qualitative similarities were observed between both DNS and CMO 96 data. Visible coherent concentrations of positive vorticity are observed near the bed in the NLIW lee in the CMO 96 data (Figure 3c). Vortices of opposite sign (such as that observed at 3 mab on JD 242.235 in Figure 3c) suggest the presence of vortex pairs ejected by the separated wave NLIW-boundary layer. The location and amplitude of these coherent vorticity concentrations do not agree with the predictions of the location of NLIW-induced near-bottom vorticity sign reversal by a simple inviscid model (Bogucki and Garrett 1993).

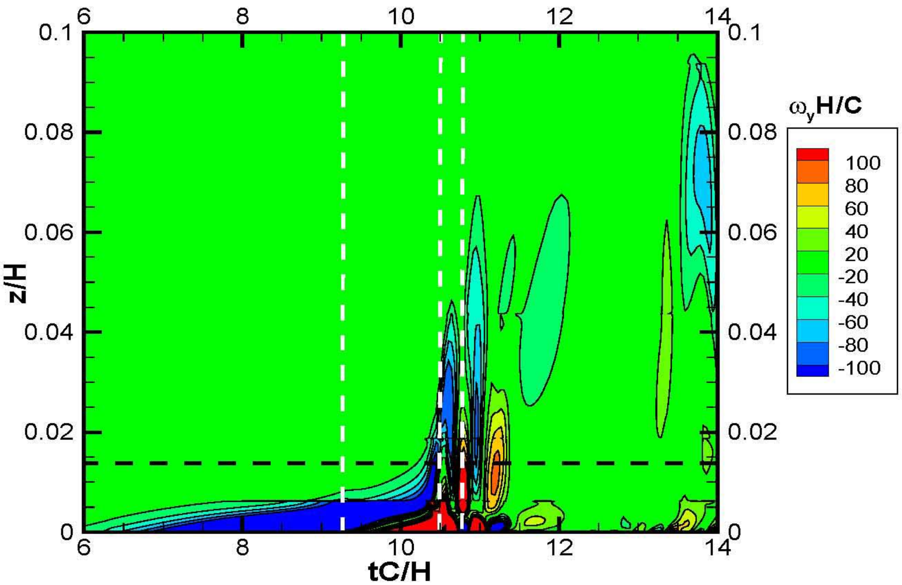

Figure 2: Eulerian depth-time diagrams of vorticity (colored contours) for DNS data. [The data correspond to the NLIW of depression shown in figure 1 and are obtained from a virtual Eulerian sensor located at x/H=-4 in a fixed reference frame (vertical dashed line in figure 1). The horizontal dashed line corresponds to its counterpart in figure 1. Shown is the bottom 10% of the water column. At t=0, the wave center is located at x/H=5. Vertical dashed lines correspond to three times shown in figure 1.]

This inconsistency between the simple inviscid model and observed near-bed vorticity values suggest that the dynamics observed in the DNS is a plausible explanation for the observed NLIW-seafloor interactions in the CMO 96 data. The two NLIWs recorded by the SeaBASS on JD 242.21 and 242.23 have amplitudes 0.07 and 0.15, respectively. Both of these amplitudes exceed the critical value for global instability extrapolated to the field Reynolds number of 10^7 (based on the findings of Diamessis and Redekopp (2006a) and adjusted according to the laboratory observations of Carr et al. (2007) for *fully non-linear* internal waves). Thus, the distinct qualitative similarities between DNS and CMO 96 observations and the low critical wave amplitude value (approximately 10%) at oceanically relevant Reynolds numbers suggest that NLIWs capable of producing distinct benthic eruptions are relatively low-amplitude waves and occur frequently on the continental shelf.

Continuing work is focused on clarifying the three-dimensional dynamics of the unstable/turbulent wave-induced boundary layer and exploring the connections of such dynamics with recent state-of-the-art measurements of NLIW-seafloor interactions by the Oregon St. group. Fully non-linear internal waves, generated through the Navier-Stokes equations with forcing terms prescribed by the theoretical analysis of Sakai and Redekopp (2007), have now been incorporated into the DNS. A request for parallel computing time was recently submitted to ONR. Once this user time is made available to us, preliminary 3-D simulations will focus on determining the appropriate spanwise domain dimension/resolution to accommodate a physically realistic transition to spanwise instabilities and turbulence in the NLIW-induced boundary layer. Additional preliminary runs will be performed to determine the necessary resolution for capturing the Kolmogorov scale in the turbulent boundary layer.

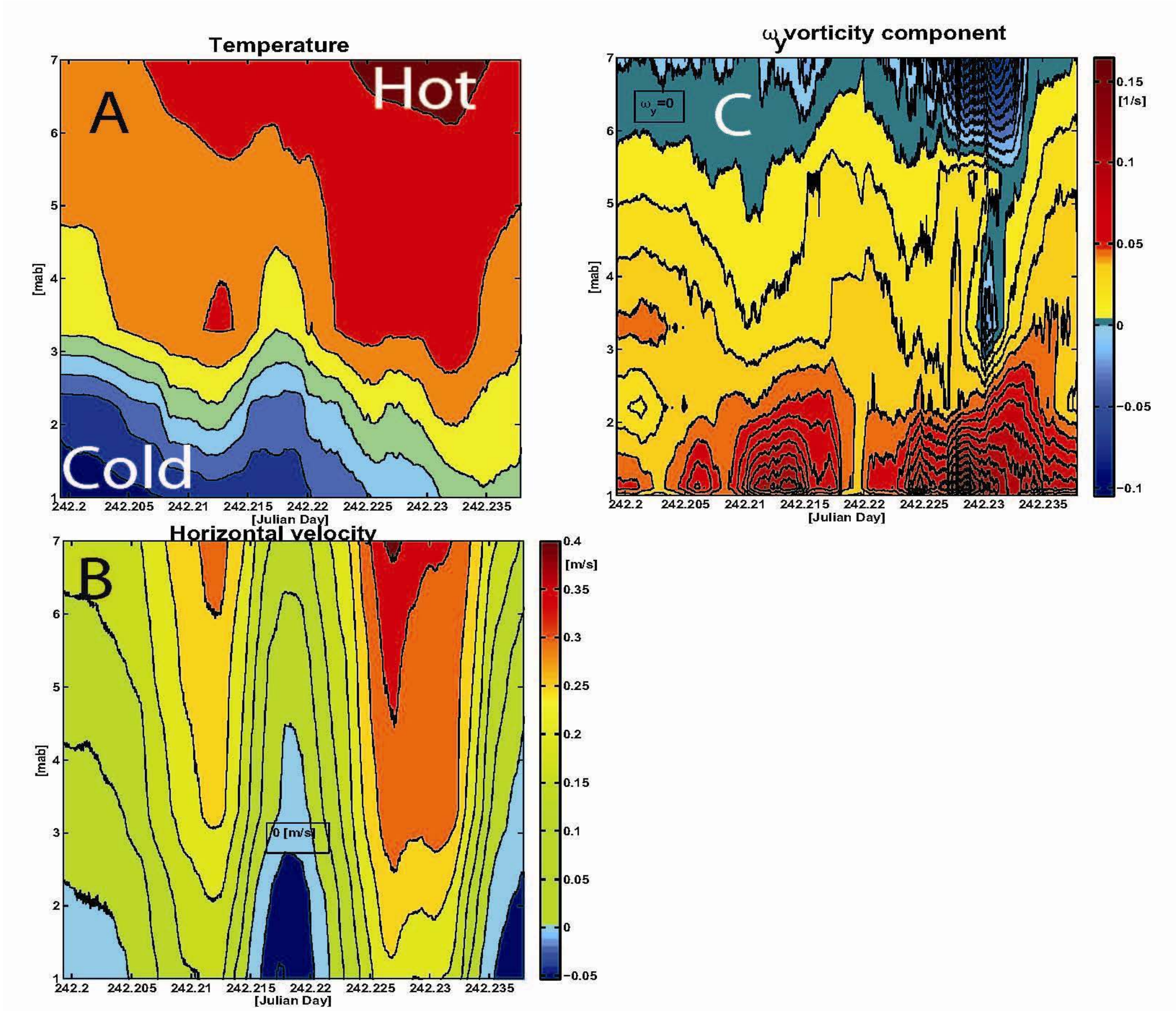

Figure 3: Details of the NLIW wavetrain passage over the SeaBASS tripod in the CMO 96 data. [Panel A - The temperature in arbitrary units: red higher, blue lower temperature within 7 m from the bottom. B- The corresponding velocity projected onto the NLIW track. The horizontal velocity projected on the NLIW track during passage of the NLIW wavetrain. The second NLIW trough passed over the tripod around JD 242.23. The light-blue shade denotes the area of negligible horizontal velocity, and consequently the extent of the separation bubble - extending to depth of 4 mab. The boundary layer undisturbed by separation and the global instability is roughly 1 m in thickness. C - Observed vorticity associated with the moving NLIW. The band zero-vorticity depth is generally between 5.5 and 7 mab in agreement with calculations from a simple inviscid steady-state model. A notable exception is seen between JD 243.23 and JD 243.235 -possibly appearance of not well resolved vortex pair.]

Three-dimensional parallel production runs will begin in December 2007. Both NLIWs of depression and elevation will be considered at specific Reynolds numbers and wave amplitudes. Our efforts will focus on characterizing the spanwise structure of the NLIW-induced boundary layer and that of the bottom shear stress field. We are interested in determining to what degree the shed vortices maintain their spanwise coherence, particularly over long times of boundary layer evolution. We also aim to identify how the development of three-dimensional effects impacts the height of ascent of coherent vortex structures, the vertical velocities observed near the bed and the temporal intermittency of benthic eruptions (Diamessis and Redekopp 2006b). Energy budget analysis will focus on dissipation rates due to NLIW-seafloor interactions. The 3-D simulations will also be equipped with virtual Eulerian ADVs spanning the lower 10% of the water column and virtual seafloor pressure sensors. Simulated dissipation rates combined with virtual ADV data will help assess the efficiency of proposed parameterizations of NLIW energy losses due to interactions with the seafloor (Perlin et al. 2005) and the energetic impact of such losses in along-path energy transport by NLIWs (Moum et al. 2007) as measured in the ONR-funded New Jersey Shallow Water 06 experiment on the New Jersey shelf. Furthermore, high-pass filtered virtual pressure sensor data can provide insight towards the signature of NLIW-induced turbulence in high-frequency seafloor pressure sensors (Moum and Nash 2007) compensated for hydrostatic pressure effects.

IMPACT/APPLICATIONS

The benthic dissipation and mixing induced by NLIWs are linked to the terminal stage of an energetic cascade process which decides the fate of the large-scale energy input into the ocean and tides. Accurate parameterization of these mechanisms of NLIW energy is of paramount importance for the reliable performance of operational coastal ocean models. The unstable/turbulent boundary layer in the footprint of a NLIW can drive significant resuspension of biogeochemical constituents which impacts directly ocean optics and acoustics and the functionality of near-bed instrumentation. The current work will provide further insight into the physical mechanisms of the above dissipative and resuspension processes, their signatures in field observations and their implications for operational forecast modeling and remote sensing.

RELATED PROJECTS

A graduate student, Jorge Escobar-Vargas, supported by internal funds and supervised by the PI is currently developing a spectral *quadrilateral* multidomain penalty method solver for high Reynolds incompressible flows in doubly non-periodic domains. Code completion is anticipated for late summer 2008 and further funding has been applied for by the PI through the NSF-OCE CAREER Award. Availability of such a solver will enable the investigation of the shoaling of NLIWs over gentle slopes (i.e. propagation over *variable depth*), with a focus on modal interactions and their effect on benthic excitation mechanisms. A collaboration with Prof. Todd Cowen (Civil & Env. Eng., Cornell) has led to a deployment of a number of thermistor chains in Cayuga Lake, aimed towards documenting the nonlinear internal wave weather in this prototypical lake. Analysis of deployment data is underway, with Prof. Leon Boegman (Civil & Env. Eng., Queens Univ., Canada) serving as a technical consultant. The P.I. is co-advising a graduate student of Prof. Boegman's in using MIT-G.C.M. to model the internal wave field in Cayuga Lake. Later stages of this collaboration will involve using the quadrilateral multidomain code under development to investigate the breaking of NLIWs on steep slopes.

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PUBLICATIONS

Submitted:

Bogucki, D.J., Diamessis, P. J. and Redekopp, L.G. Numerical investigation of solitary internal wave-induced global instability in shallow water benthic boundary layers, to ***J. Phys. Oceanogr.*** .

Diamessis, P.J., Lin, Y.C. and Domaradzki, J.A. Effective numerical viscosity in spectral multidomain penalty method-based simulations of localized turbulence, to ***J. Comp. Phys.* .**